DESIGN AND CONSTRUCTION OF PLASTIC GEOCELLULAR RAIN WATER HARVESTING/STORMWATER DETENTION TANKS

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ABSTRACT

Plastic voided modular structures (known as geocellular units) were first used in the mid-1980s in Europe below pavements to store stormwater. Its use has since spread to rainwater harvesting and on-site stormwater detention for residential, commercial and industrial developments. It is an environmentally friendly and sustainable solution. However, there are engineering pitfalls associated with the design and construction of plastic geocellular structures. The main pitfalls are associated with creep rupture of plastic structures, potential construction damage and the lack of care in wrapping the cells with filter fabric and backfilling procedure. As the scale and complexity of geocellular structures have significantly increased in recent years, guidance on appropriate design and construction methods has become more essential for these structures to be adopted as safe, yet economic and sustainable solutions.

In this paper, the author will describe his design and construction experience based on research associated with a court case on the damages associated with a major geocellular on-site stormwater detention project (approx. 8.5 Mega litres), and recent conversion of his backyard swimming pool to a 40,000 litre rainwater harvesting tank. References on design and construction guidance will be described together with the author's personal opinion on the use of partial factors in the economic design of geocellular structures.

1. INTRODUCTION

The use of geocellular units for on-site stormwater detention and rainwater harvesting has gained popularity and momentum in the last decade or so. They are more economical than conventional precast concrete structures, and considered to be environmentally friendly and sustainable solutions because of their lower embedded carbon footprint. The energy required to produce plastic is only a fraction of that for precast concrete, and the installation effort is also less due to the significantly lighter weight of plastic geocellular units. The use of recycled plastic, with adequate quality control, provides further environmental and sustainability benefits.

For the above reasons, the scale of geocellular structures are getting larger. However, their design is not trivial, and involves understanding of material type and behaviour, structural and geotechnical engineering design principles, and good construction practice. The lack of good practice in any of the above can potentially lead to disastrous consequences. The following paragraph is a quote in the Summary of CIRA C737 (2016):

> *"Because of their size and below ground location many geocellular unit installations are now significant geotechnical and structural engineering designs with potentially severe consequences if failure occurs."*

In keeping with the current drive for more sustainable solutions, recycled plastic has been introduced in the production of geocellular units. This gives rise to greater variability in the properties of the plastic product to the point that they may have similar variability as geotechnical materials compared to other man-made building materials such as steel and concrete. Quality control in manufacturing including appropriate forms of testing and incorporation of material variability in the selection of design parameters is essential. Furthermore, although these units are light and easy to install manually, they are can be damaged if there is a lack of care during handling, installation and inappropriate post-installation construction activities.

Due to the lack of published data, the creep rupture properties of plastic often plays one of the most influential factor in the design of geocellular structures.

2. DESIGN AND CONSTRUCTION GUIDELINES

Schematics for stormwater geocellular structures in infiltration (Figure 1), storage and attenuation (Figure 2) modes are illustrated by Woods-Ballard et al (2007) as reproduced below.

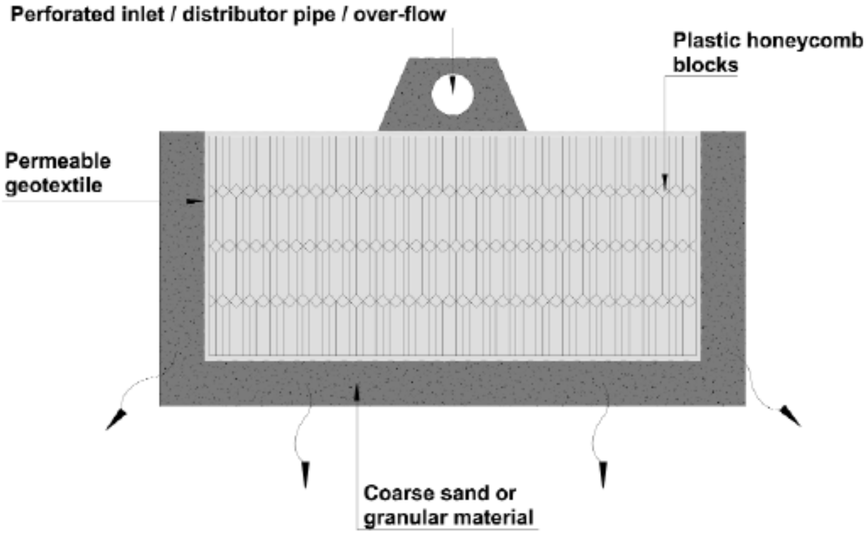


Figure 1: Infiltration system (Woods-Ballard et al, 2007)

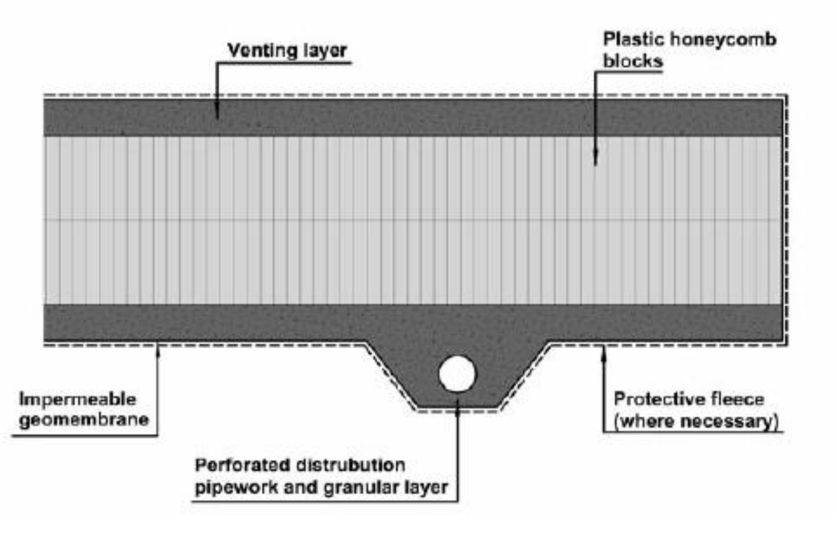


Figure 2: Attenuation or storage system (Woods-Ballard et al, 2007)

Infiltration, attenuation or storage structures are similar in that the geocellular units form a voided structure to hold the stormwater, and differ only in whether an impermeable geomembrane is used, and pipe work details.

Depending on the amount of soil cover and surface loading requirements, the geocellular units come in different construction types, geometry and strength grades. The most common types are those assembled from rectangular flat plates with increasing numbers of internal plates to provide higher load capacity as shown in Figures 3a and 3b. The plates are moulded with lugs that push together similar to Lego blocks. The assembled units are then clipped together to form a structure to the desirable size. The units are manufactured to different dimensions and can be stacked together without intermediate bottom plates to form double or triple units up to about 1.35 m to 1.5 m or more in height.

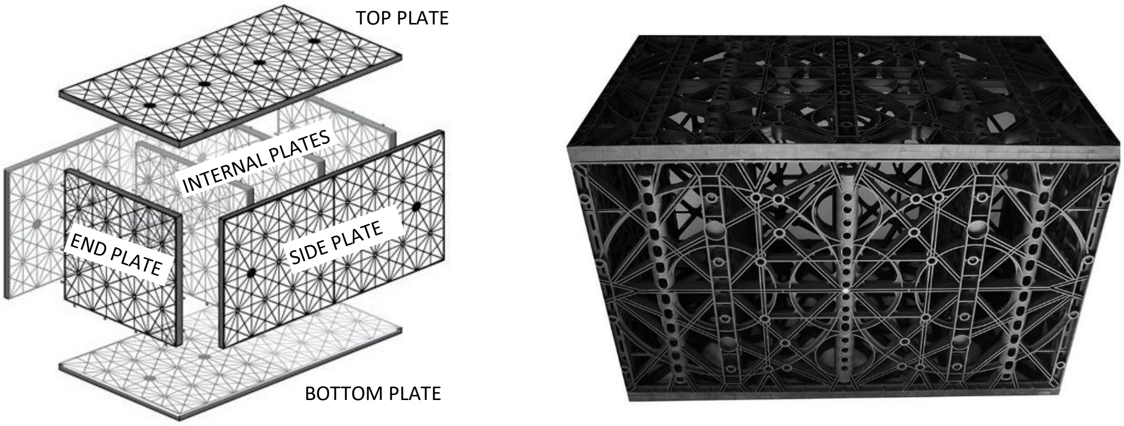


Figure 3: Geocellular unit, (left) exploded view of geocellular unit, and (right) assembled unit[1] (see Note 1 in Figure 4)

Where the application requires high load bearing, units with injection moulded internal columns are generally used as shown in Figure 4.

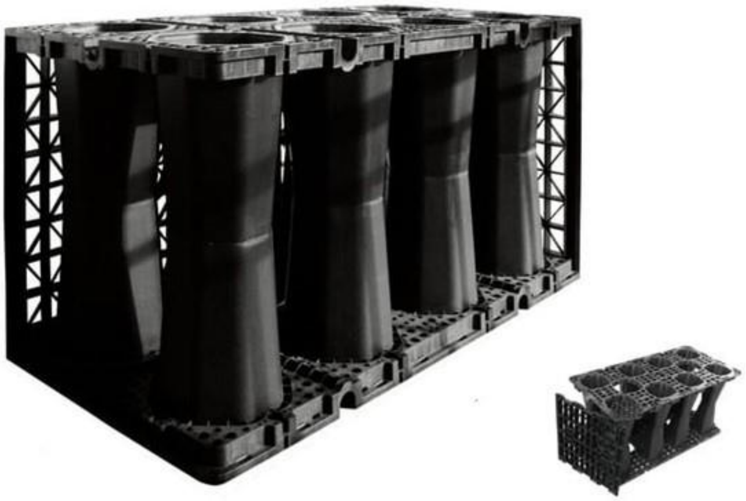


Figure 4: High load bearing geocellular unit[1]

[1] NOTE: Class B geofabric has grab strength approximately 30% less than Class C (see Table RM63A5.2 for full details of geotextile filter fabric strength classes)

The design process for geocellular structures should include the following considerations:

- Type of application (i.e. soakage, infiltration, attenuation, harvesting, storage etc).
- Geometric requirements.
- Ground conditions including groundwater and chemical environment.
- Loading requirements, including design life and creep rupture strength, construction loads.
- Selection of raw material (e.g. polypropylene, polyvinyl chloride, low density and high density polyethylene).
- Selection of impermeable membrane (if required) and filtration geotextile.

Testing of product strength is essential and allowance must be made for statistical variability of plastic products. If it is contemplated to use recycled plastic in the production of the geocellular units, greater attention should be paid to quality control and testing of different batches during the production process.

The geotechnical and structural design of geocellular structures requires knowledge of soil structure interaction, and in particular the distribution of vertical pressure from surface loading which may include soil cover, pavement (if any) and type of building, vehicle or rail loads, and lateral earth pressure loading from backfill and adjacent surcharge. Construction loads must also be considered. Of particular importance is the careful manual placement of sufficient thickness of sand or fine gravel cover over the units prior to allowing construction vehicle loading over the units. Backfilling uniformly on all sides of the units is also critically important to avoid excessive lateral deformation and/or damage to the units.

Guidelines for the design and construction of geocellular structures are well established and include Wilson et al (2004), Woods-Ballard et al (2007), Wilson (2008) and O'Brien et al (2016). The readers are urged to consult these references before embarking on such projects.

3. CREEP RUPTURE AND LIMIT STATE DESIGN

Creep rupture in geosynthetic products (e.g. geogrids and high-tensile strength geotextile soil reinforcement fabrics), and fiberglass bolts is a well-established phenomenon, but there is very limited published data on this topic for geocellular units. This section presents some information on creep rupture testing data on units that have been exhumed from a site where a large geocellular structure (approx. 8.5 Mega litres stormwater detention project) was installed.

Creep rupture is a time dependent behaviour of a material under sustained loading, with increasing strain over time (creep) eventually leading to failure (rupture) as illustrated in Figure 5 below.

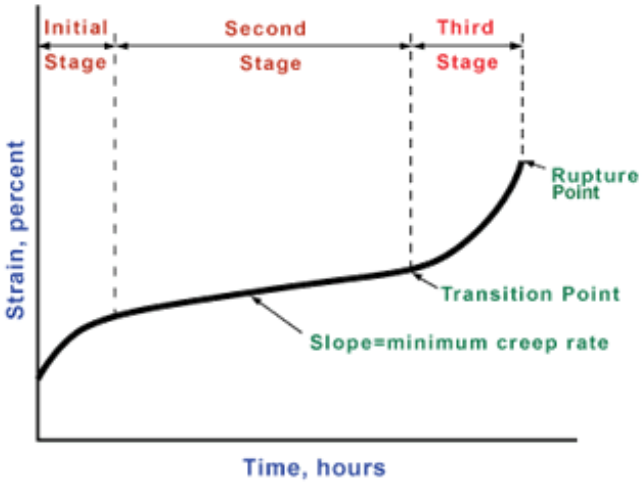


Figure 5: Typical creep rupture behaviour
(courtesy of https://www.nde-ed.org/EducationResources/CommunityCollege/Materials/Mechanical/Creep.htm)

For polymer materials under sustained tension, creep rupture may be incorrectly considered as a cross sectional area reduction (or "necking") problem due to Poisson's Ratio effect. The mechanism of creep rupture is in fact far more complex. Under a sufficiently high constant stress (but well below the short-term yield stress), the polymer chains are in fact uncoiling and begin to slip past each other. This effect is more pronounce at higher temperature. Therefore, compression members also undergo creep rupture. The author's opinion is that the creep rupture mechanism in geocellular structures can be even more complicated than a member in pure tension. This is because both the horizontal and vertical plates are under bending stresses, and the vertical plates can also undergo buckling failure. The complex loading of the plates can also lead to delayed internal fracturing of the plastic.

When combined with the greater potential for the damage of plastic materials during construction, creep rupture often becomes the governing factor in design. The Australian Standard, HB154-2002 discusses the difference between the "Available" and "Required" strength properties to allow for sufficient safety factor for the application of geosynthetics which also includes "geocontainers". Figure 1 of HB154-2002 is reproduced as Figure 6 below, which clearly shows the reduction of safety margin with time.

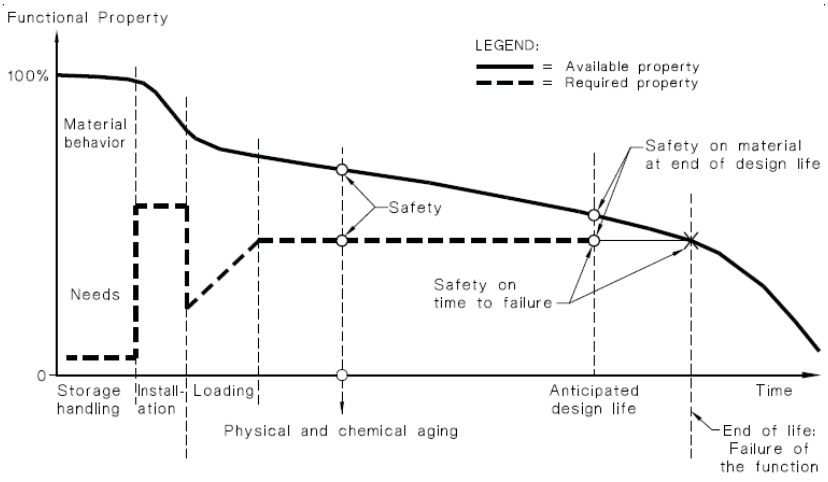


Figure 6: Available and required values as a function of time (AS BH154 – 2002)

The Limit State Design approach for geosynthetic materials such as those described in BS8006-1:1995 and AS4678 – 2002 requires the following inequality to be met:

$\Psi_1 G + \Psi_2 Q \geq (\phi_1 \text{ x } \phi_1 \text{x } \phi_1 \text{ x } \phi_1 \ldots\ldots) \text{ x } \phi_n \text{ x } R_{st}$ Equation [1]

where:

G = Dead Load (sustained)

Q = Live Load (transient)

Ψ_1 = Load factor on dead load

Ψ_2 = Load factor on live load

ϕ_1, ϕ_2, ϕ_3 …etc. are material strength reduction factors. Using the terminology in AS4678, they are defined as follows:

ϕ_{up} = reduction factor for manufacture variability

ϕ_{ri} = reduction factor for installation damage

ϕ_{rt} = reduction factors for environmental change in thickness (e.g. corrosion)

ϕ_{rs} = factors for environmental change in strength

ϕ_{rs} = factors for environmental change due to temperature

ϕ_{ud} = reduction factors for uncertainty in environmental degradation

ϕ_{rc} = reduction factor for creep rupture

ϕ_{uc} = reduction factor to account for uncertainty in extrapolation of test data on creep rupture, and is dependent on the length of time testing data is available.

ϕ_n = structure importance reduction factor to provide additional safety margin for structures of different importance, in particular with respect to post-disaster (e.g. earthquake) recovery functions

R_{st} = Either a “guarantee minimum” or “characteristic value” as determined from testing.

Manufacturers of geosynthetic products usually publish recommended reduction factors including creep rupture reduction depending on the extent of testing available. For geocellular units, there is very little published information on these reduction factors and designers may have to resort to published design guidelines such as those summarised in Table 1.

Table 1: Guideline strength reduction factors

Reduction Factor	**AS4678:2002**	**HB154:2002**	**BS8006-1995**
ϕ_{up} – manufacture	0.95 if R_{st} is characteristic value 1.0 if R_{st} is a guaranteed minimum	0.95 if R_{st} is characteristic value 1.0 if R_{st} is a guaranteed minimum	0.95 if R_{st} is characteristic value 1.0 if R_{st} is a guaranteed minimum
ϕ_{ri} – installation damage	0.6 to $0.9^{(1)}$	Could be as low as 0.5	Depending on fill type and installation procedure$^{(4)}$
ϕ_{rt} – environmental change thickness	0.9 to 1	Not used	Dependent on fill type and exposure condition$^{(4)}$
ϕ_{rs} – environmental change strength	0.5 to 0.9	Project specific relating to UV exposure	
ϕ_{rst} – environmental change temperature	Function of temperature	Function of temperature Generally > 0.9	
ϕ_{ud} – uncertainty in environmental degradation	0.8	Not used	
ϕ_{rc} – creep rupture reduction	$0.19^{(2)}$	Could be as low as 0.17	To be based on test results$^{(4)}$
ϕ_{uc} – extrapolation factor for creep rupture	1.25-0.25N$^{(3)}$	Could be as low as 0.5	1.5-0.5N$^{(3)}$

Notes:

(1) Dependent on particle size of soil placed against geosynthetic (0.8 to 0.9 for fine sand, to 0.6 to 0.9 for coarse gravel

(2) Extrapolated for 50 year design life from values of 0.2 for 30 years to 0.17 for 100 years

(3) N is the number of log cycles of time extrapolation of creep data to the design life

(4) BS8006:1995 provides recommendations on using reduction factors given in manufacturer’s datasheets based on trials

The problem with adopting combinations of the guideline strength reduction factors shown in Table 1 is that the net resultant design value could be as low as only 5% of the short-term test strength. Creep rupture contributes to the greatest reduction, particularly if there is no such testing carried out.

On the other hand, while there may be little redundancy in the application of a single layer of geosynthetic tensile fabric in a reinforced soil layer (e.g. for strengthening of working platforms), the application of geocellular structures usually give rise to significantly greater redundancy due to the multi-unit arrangement, and therefore the combined use of installation damage factor with creep rupture reduction may be unrealistic and will likely result in an overly conservative design. In the author’s opinion, the geocellular units are less prone to damage than tensile fabrics provided they are handled with care during transport and installation, and a sufficient thickness of protective layer of granular material is placed manually over the installed units prior to trafficking by machinery.

In a case study which involved the installation of a large scale stormwater detention tank in NSW using geocellular units, installed cells were exhumed and both short and long-term creep testing were carried out.

The creep rupture testing was carried out by sustained load tests at different percentage of the short-term ultimate load and measuring the time to failure. The results of this testing are presented in Figure 7.

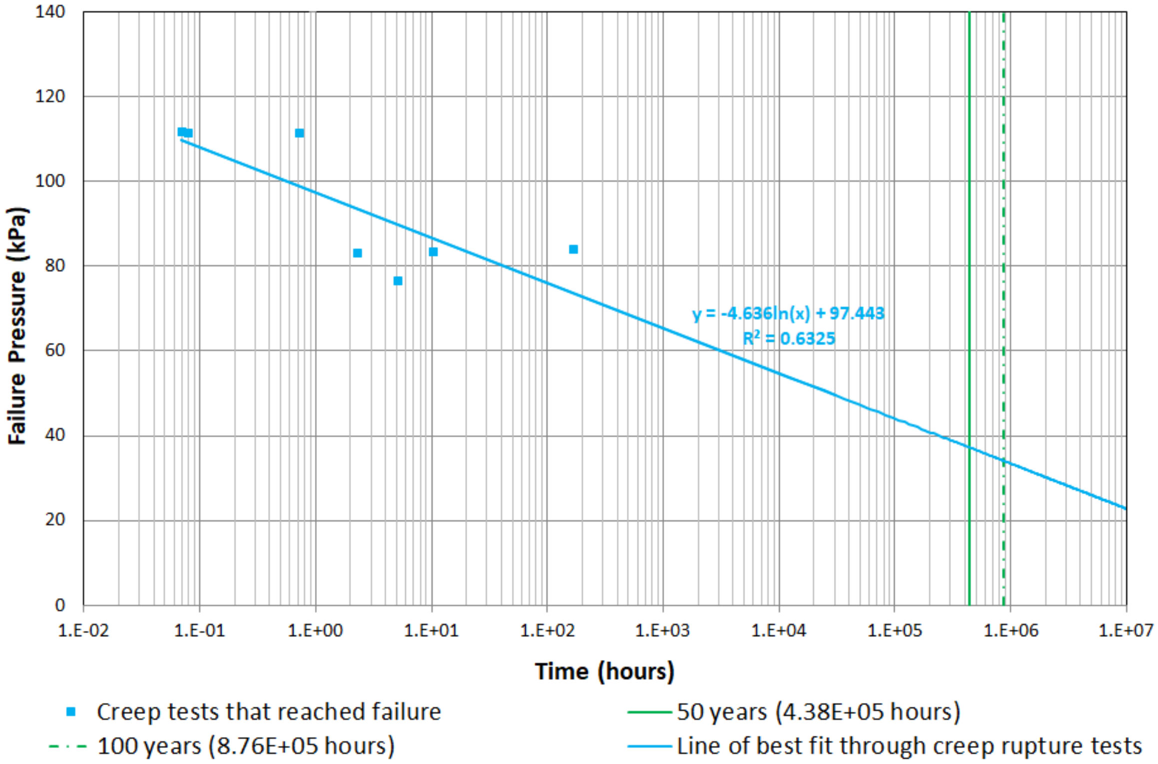


Figure 7: Creep rupture test results from a project in NSW (exhumed cells)

It can be seen from Figure 7 that the short-term compressive strength of the tested units is about 110 kPa, with an extrapolated failure strength of about 37 kPa at 50 years and 34 kPa at 100 years (i.e. about 34% and 31% of the short-term strength). There were also some test results at 50% of the short-term strength that were extended to 5,500 hours which did not reach creep rupture. For a design life say of 50 years, the creep extrapolation factor with 5,500 hours of testing based on the equation given by AS4678 would give $\phi_{uc} = 1.25 - 0.25N = 0.78$ where $N = \log(4.38 \times 10^5/5{,}500)$ giving a design long-term strength at 50 years of 26.5% of the short-term test strength. This is over 5 times higher than 5% of the short-term strength that would otherwise have been assessed using published guideline recommendations without testing, and clearly demonstrates the importance and benefits of having long-term test data.

It should be stressed that Figure 7 represents testing on only one particular product, with samples exhumed a few years after installation. This figure is provided as an indication only and should not be used for generic design purposes. For major projects, the author recommends long-term testing data be obtained for the specific product to be used, together with project specific testing regime including product quality control testing during construction.

4. SWIMMING POOL CONVERSION PROJECT

At the site, it was decided to convert a 60,000L swimming pool to an underground rainwater harvesting tank by installing a geocellular structure inside the existing pool. The concrete lining of the pool walls and base provided the water retention function so a geomembrane was not necessary. The design and construction comprised the following features:

Geocellular units –	Polypropylene lattice plate construction with four internal vertical plates
	Double units measuring 1030 mm (H) x 800 mm (L) and 490 mm (W)
	Single units measuring 530 mm (H) x 800 mm (L) and 490 mm (W)

Minimum short-term compressive strength = 91 kN (or 232 kPa on top plate) and rated at 35 kPa long-term.

Geotextile filter fabric – Class C (according to RMS RM63 grading) with 300 mm overlap glued down using silicon sealant.

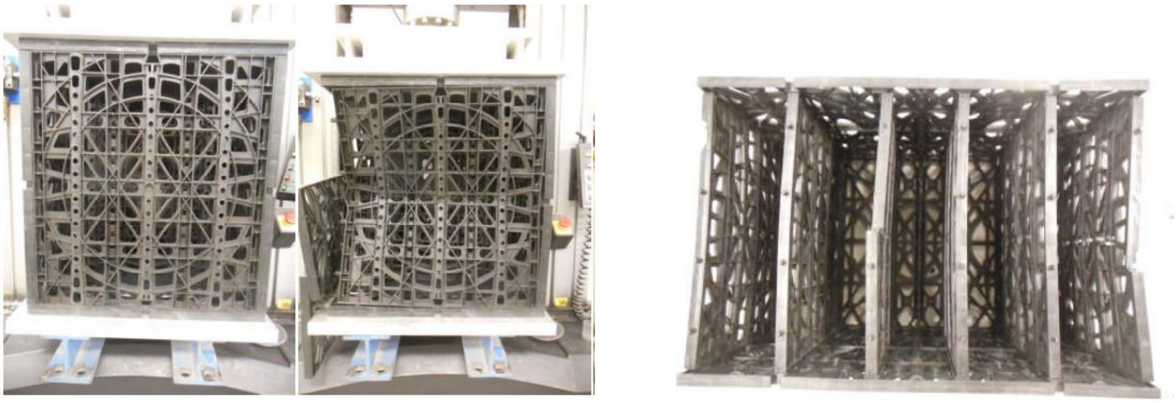
Backfill – Initial layer of < 1MPa LiquiFill levelling layer (refer Hanson Australia website for details https://www.hanson.com.au/products/concrete/fills/liquifill/

10 mm nominal size recycled concrete and brick aggregate around the sides and up to 360 mm above the top of the units.

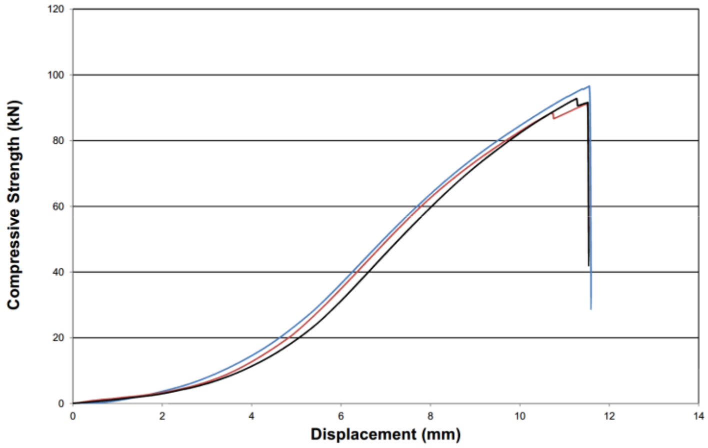
Surface finishing – 40 mm thick x 10 mm nominal size river gravel confined in Copolymer Polypropylene geocells.

The individual unit (12.7 kg for each single unit and 23.5 kg for each double unit) was easy to manually assemble and the only equipment required was a rubber mallet to drive the plates (with moulded lugs) together. Prior to laying the geotextile fabric, preparation of a level surface was found to be a crucial step. Care in this step enables rapid installation of the unit together to form the final structure with no gaps between units and to minimize any stress concentrations using the backfilling operation.

The supplier of the units provided short-term load test results which are reproduced in Figure 8 below.



(a) Pre-test (end view) (b) Post-test (end view) (c) Post-test (top view)



(d) Load-displacement Result

Figure 8: Test results of units provided by the supplier for the pool conversion project

According to the test report provided, the compression testing was conducted on an Instron Model 5885 Tensile/Compression Testing Machine using parallel plate loading at a rate of 2.0% of the height of the chamber per minute in accordance with ASTM F2418 (2013).

It can be seen from the load-displacement curves and post-test photographs shown in Figure 8 that the units failed in a brittle manner. Once the failure load was reach, the plastic plates exhibited cracking and buckling, leading to rapid collapse of the units. Unfortunately, the supplier did not conduct any long-term creep rupture testing. There was no sign of settlement 6 months after completion of the geocellular rain harvesting tank.

A total of 75 double cells and 35 single cells were installed. Care was taken to ensure that no damage of the units occurred during installation. The use of 4 internal vertical plates proved to give a much more robust structure against bending of the top plates during the filling process. The incremental cost of 4 internal plates versus 2 was relatively minor (< 5% of the unit cost). For the size of backfill aggregate used, a Class B[1] filter fabric would have sufficed but the incremental cost for a Class C[2] fabric was relatively small to give greater resistance to potential installation damage. Sealing of the filter fabric overlaps using silicon sealant was quick and easy, and relatively economical to provide ease of mind to improve long-term performance. Backfilling around the sides of the completed cells was carried out in a manner that limits the fill level difference to within 0.4 m on opposite sides of the structure. Some photographs of the installation process are presented in Figures 9 to 14.

Figure 9: Placement of liquifill levelling layer

Figure 10: Double units and geofabric wrap

Figure 11: Backfilling around double units

Figure 12: Single units at shallow end

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[1] Class B geofabric has grab strength approximately 30% less than Class C (see Table RM63A5.2 for full details of geotextile filter fabric strength classes)

Figure 13: 40 mm thick geocell finishing layer

Figure 14: Finished installation

5. CONCLUSIONS

The use of plastic geocellular structures as a stormwater detention or rainwater harvesting solution is an environmentally friendly and sustainable engineering alternative to traditional concrete structures. This paper demonstrates the importance of conducting long-term creep rupture testing for design. Significant savings can be derived for large projects using geocellular units if long-term creep rupture testing data is available instead of having to rely on potentially overly conservative strength reduction and creep extrapolation factors.

Care in construction is important and may also be utilized to lessen the reduction in design strength to account for installation damage in combination with creep rupture. This comment also applies to the selection of the robustness of the units for installation, geotextile grade, and overlapping details, which all affect the long-term performance of geocellular structures.

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